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Myers et al.

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(54) **CURRENT-CONTROLLED CARRIER TRACKING FILTER FOR IMPROVED SPURIOUS SIGNAL SUPPRESSION**

(75) Inventors: **Brent A. Myers**, Palm Bay; **Paul J. Godfrey**, Melbourne, both of FL (US)

(73) Assignee: **Intersil Corporation**, Palm Bay, FL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

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(22) Filed: **Jun. 17, 1999**

Related U.S. Application Data

(63) Continuation of application No. 08/606,958, filed on Feb. 23, 1996.

(51) **Int. Cl.**⁷ **H04L 27/06**

(52) **U.S. Cl.** **375/344; 375/324; 375/343; 375/361; 327/17; 327/74**

(58) **Field of Search** **375/344, 324, 375/343, 361; 331/17, 74; 327/552, 553, 558**

(56) **References Cited**

U.S. PATENT DOCUMENTS

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Primary Examiner—Stephen Chin

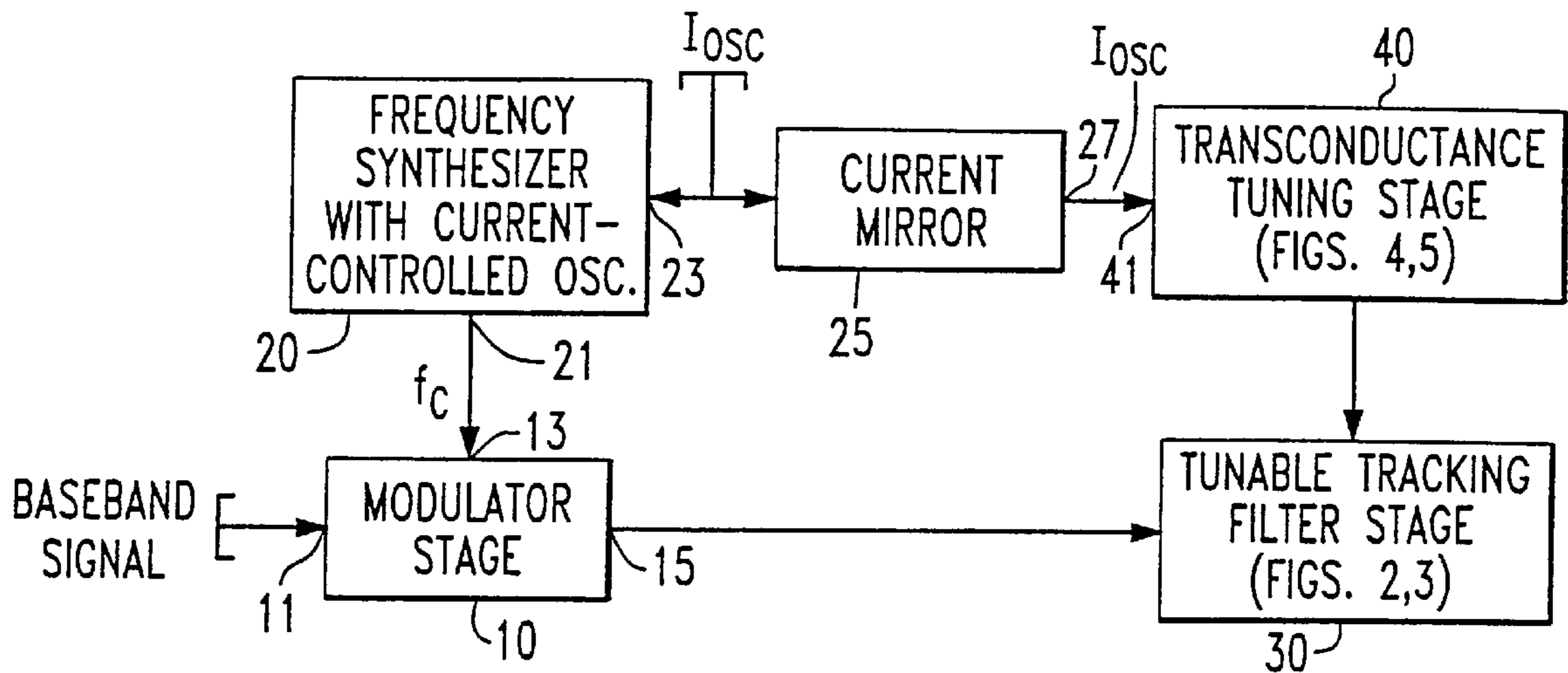
Assistant Examiner—Shuwang Liu

(74) *Attorney, Agent, or Firm*—Allen, Dyer, Doppelt, Milbrath & Gilchrist, P.A.

(57) **ABSTRACT**

Spurious energy suppression for a data communication system is achieved without using a large order noise suppression filter, by means of a post-mixer tracking filter that contains a current-controlled MOSFET-implemented resistance for a transconductance-capacitance filter and an associated transconductance tuning stage. The MOSFET-implemented resistance is controlled by the same control current that establishes the output frequency. As a result, the cut-off frequency of the tracking filter is linearly proportional to the carrier and independent of absolute processing parameters and temperature.

16 Claims, 2 Drawing Sheets



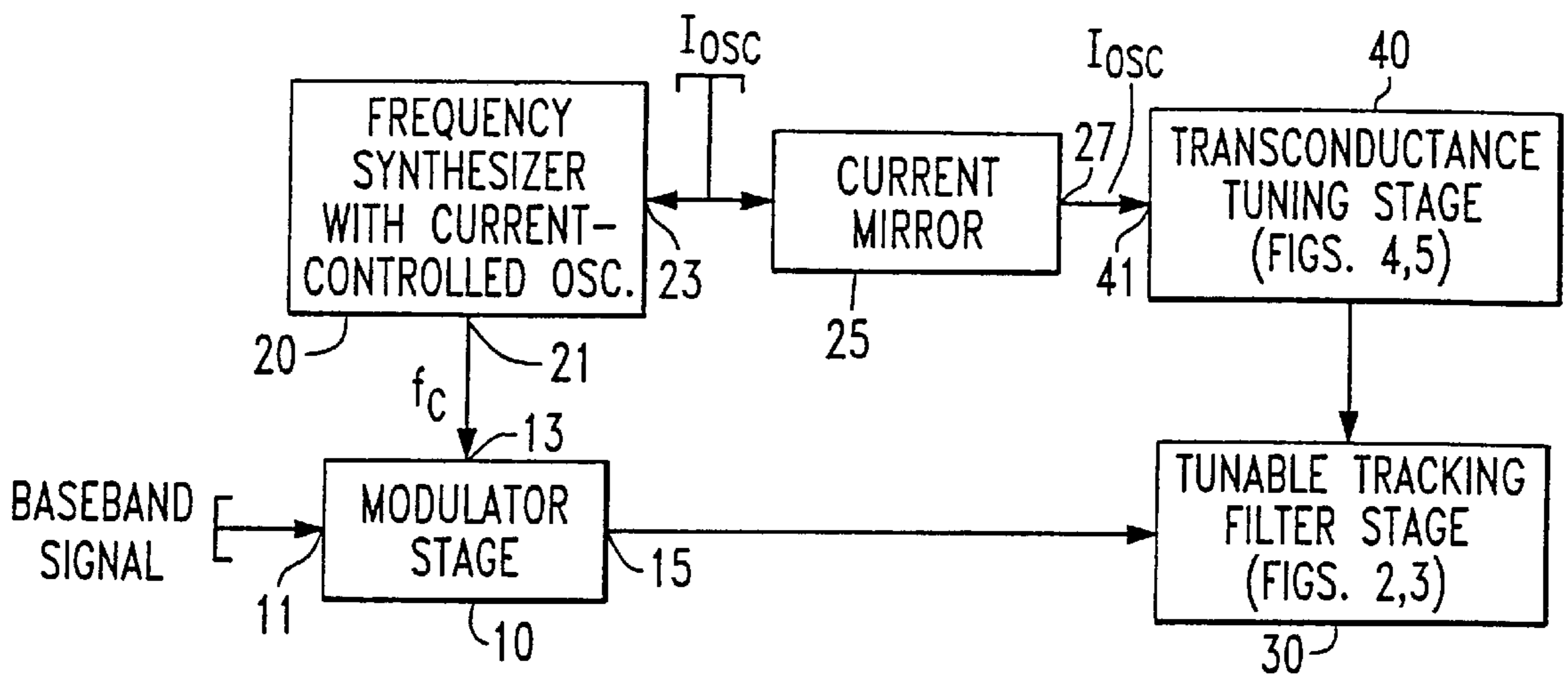


FIG. 1

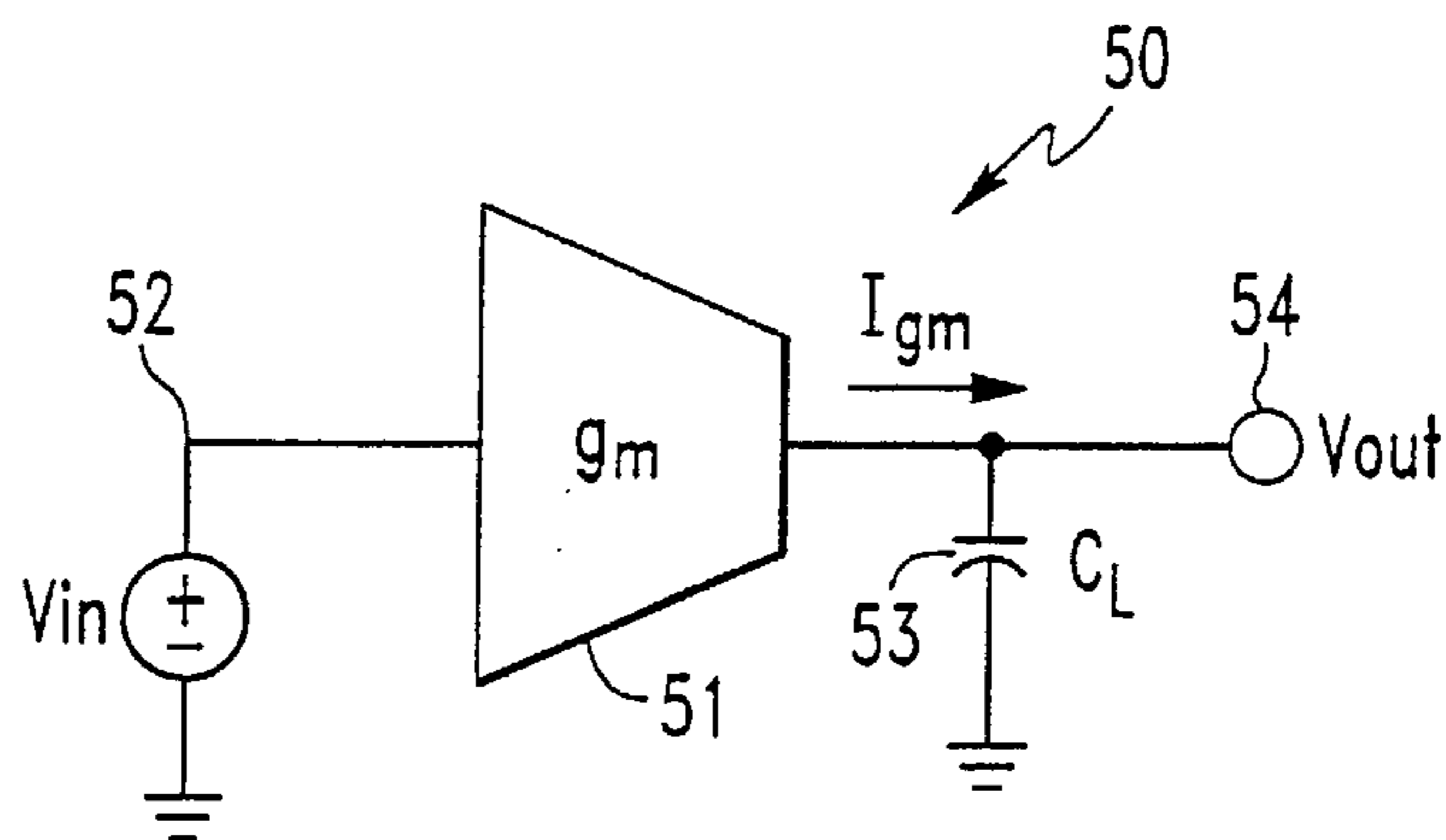


FIG. 2

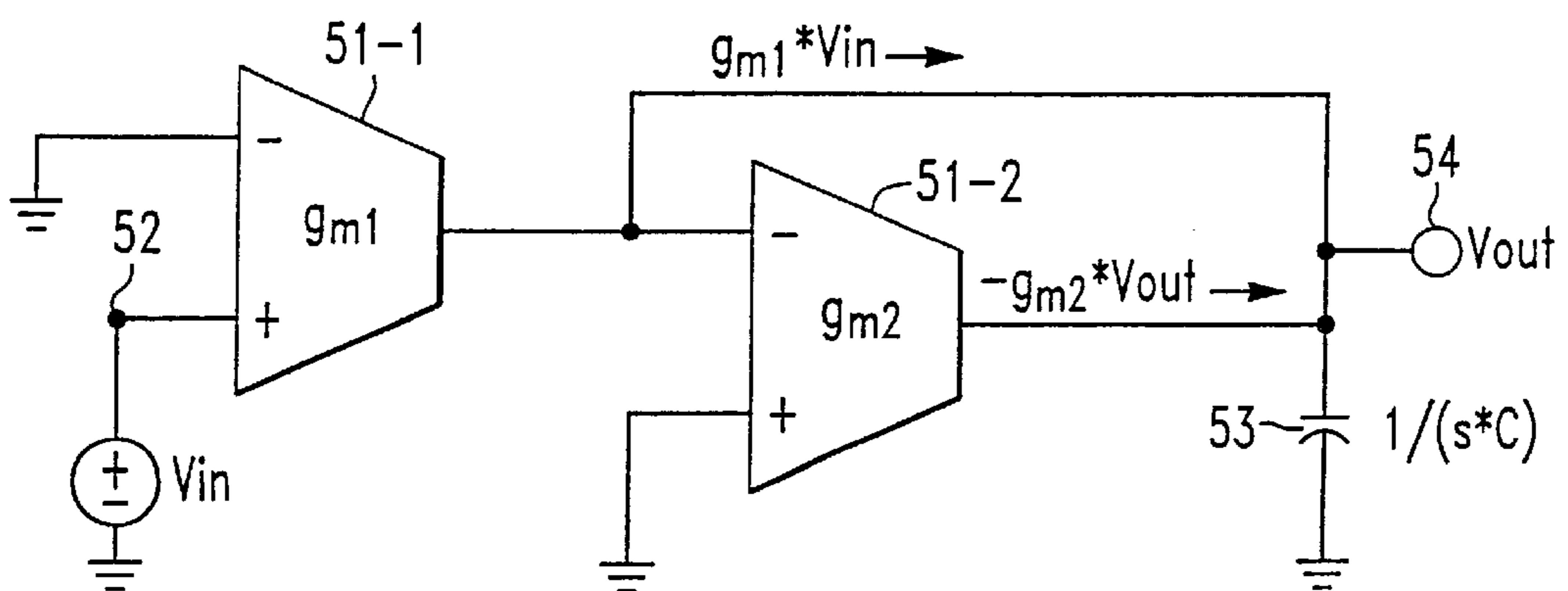


FIG. 3

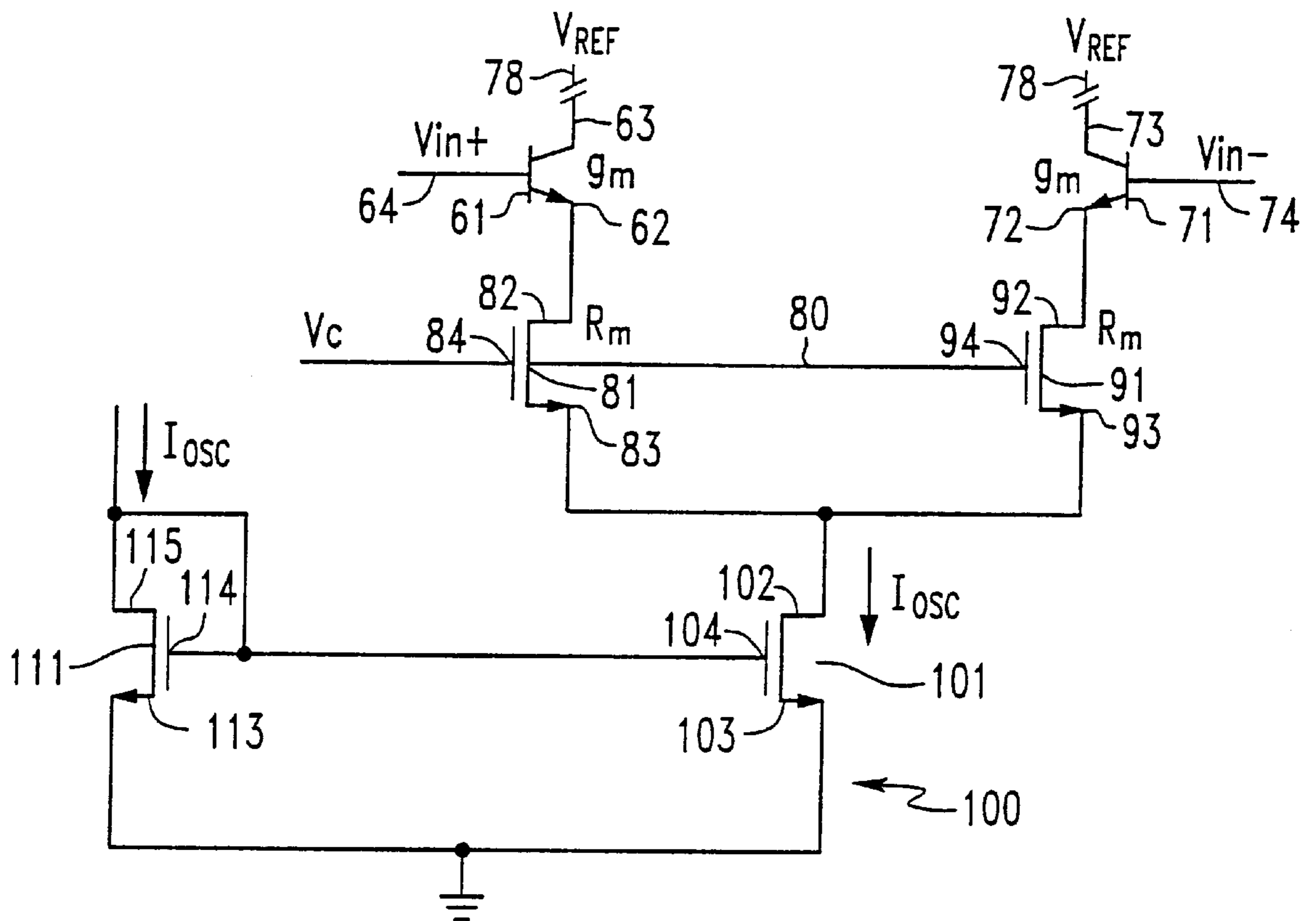


FIG. 4

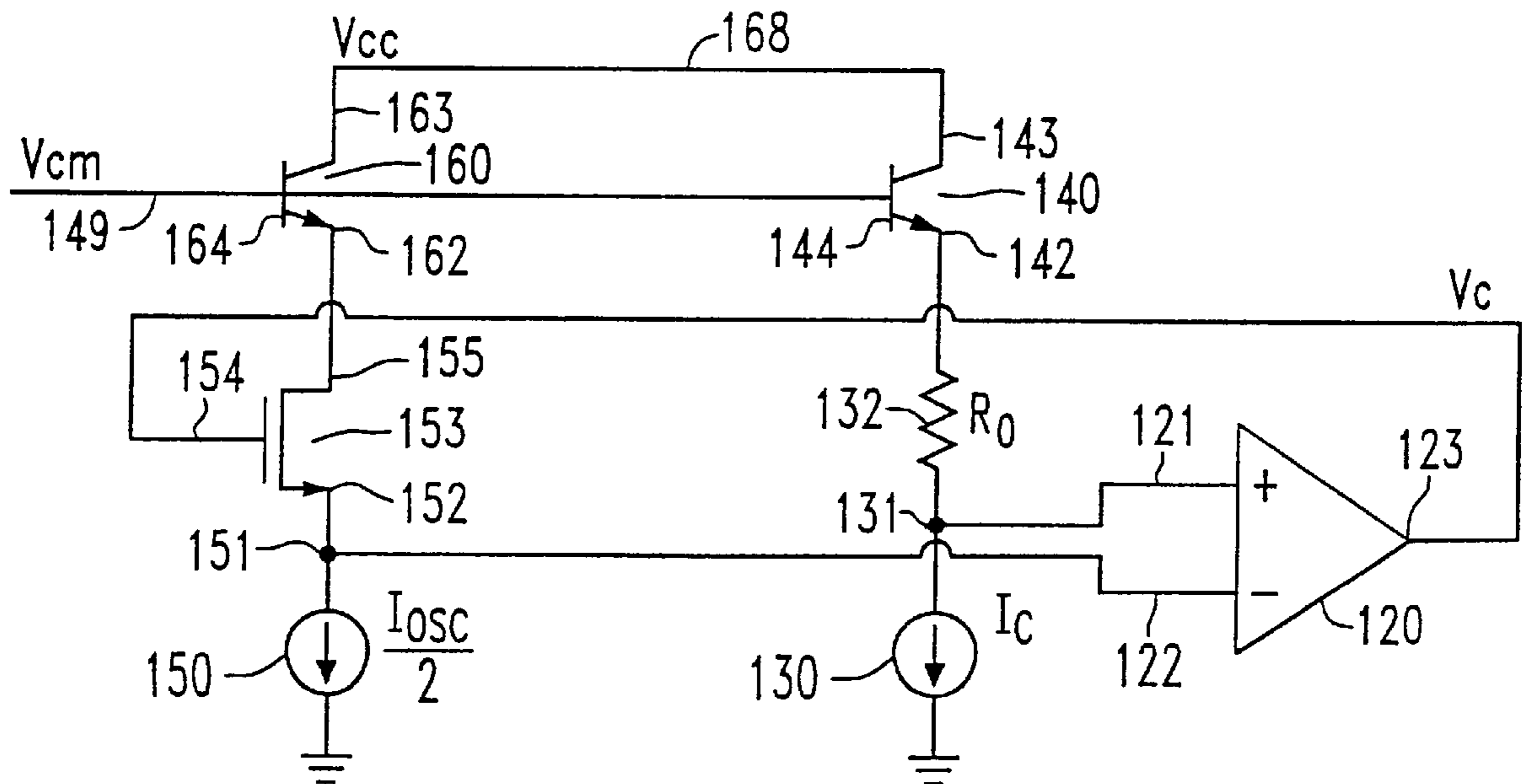


FIG. 5

CURRENT-CONTROLLED CARRIER TRACKING FILTER FOR IMPROVED SPURIOUS SIGNAL SUPPRESSION

This is a continuation of application Ser. No. 08/606,958, filed Feb. 23, 1996—pending.

FIELD OF THE INVENTION

The present invention relates in general to communication circuits, including continuous time integrated communication circuits, and is particularly directed to an improved on-chip, 'carrier-tracking' filter circuit, having a cut-off frequency that varies linearly with a control current supplied to a current-controlled oscillator, from which the carrier frequency to be tracked is derived.

BACKGROUND OF THE INVENTION

One of the requirements currently imposed (by the FCC) upon communication systems and networks is that they comply with very stringent spurious energy suppression standards. In today's digital communications environment, data signals (which have square rather than sinusoidal characteristics) are typically conditioned and modulated upon a higher carrier frequency (e.g., via emitter coupled logic circuitry (ECL)-based in-phase I and quadrature Q channels) where the data can be more readily transmitted.

Since the primary signal energy component of interest is located in the spectrum immediately surrounding the carrier center frequency, other spurious energy—typically the odd harmonics (multiples) of the original carrier frequency resulting from the modulation (multiplication or mixing) operation of such non-sinusoidal signals—must be removed, in order to avoid contaminating adjacent carrier channels that contain their own information energy components.

One way to remove such spurious energy is to apply the mixer output to a lowpass filter having a cutoff frequency that is slightly higher than the highest carrier frequency to be employed in a given communication system, such as a frequency-agile transceiver. Unfortunately, if the highest carrier frequency capable of being generated is close to the second or third harmonic of the lowest carrier frequency in the operating range of the system, the size (order) of the filter required to achieve sufficient unwanted energy suppression under all operating conditions is unacceptably large.

As a non-limiting example, in the case of conducting data communications over a television cable network, the required harmonic suppression filter may be an eight to twelve order filter. Such a large and complex filter is obviously impractical where cost and semiconductor silicon area are prime considerations in chip design. Moreover, such a large order filter has a higher group delay error, which can increase bit error rate.

Another technique is to add a filter pole to the carrier generator prior to the mixer. For a fixed carrier, adding a single pole is readily accomplished by simply adding a capacitor; however, in the case of a frequency-agile system, it is necessary to employ a plurality of capacitors, typically implemented as a programmable (controllably switched, binary weighted) capacitor array.

If the process employed to manufacture the integrated circuit architecture is a BiMOS process, MOSFET switches may be used to switch among the capacitors of the array. However, for a multiple channel system where there are a considerable number of potential carrier frequencies—requiring a separate capacitor for each carrier frequency, a

binary-weighted capacitor array cannot be effectively employed, since the filter's cutoff frequency varies with the reciprocal of the value of the capacitor. As a consequence, if the cutoff frequency is to vary in a linear manner, the cutoff control capacitor must vary in a non-linear fashion, which not only again leads to an unacceptably large and complex filter, but the required switch array introduces parasitic poles, which are not readily compensated.

SUMMARY OF THE INVENTION

In accordance with the present invention, the shortcomings of the prior art filter proposals described above are successfully remedied by a post-mixer carrier frequency-tracking filter that contains a current-controlled MOSFET-implemented resistance for a transconductance-capacitance filter and an associated transconductance tuning stage. The current-controlled MOSFET resistance-based filter mechanism has a transfer function which is established by an oscillator control current that controls the carrier frequency of interest.

The post-mixer carrier of the invention comprises a continuous time filter circuit, in particular a tunable g_m/C filter, of the type commonly employed in high frequency telecommunication signal processing integrated circuit architectures. The fundamental building block of such a tunable g_m/C filter is an integrator stage formed by combining a transconductance (g_m) stage with an integrating capacitor. By cascading multiple integrator stages, a transconductance-C (g_m-C) filter of any desired order may be realized, having a cutoff frequency f_c that is effectively proportional to the ratio of g_m to C .

The transfer functions of each of a tunable transconductance of the MOSFET-implemented resistance of a transconductance stage-capacitance filter and an associated transconductance tuning stage are effectively dependent upon the same oscillator control current that defines the output of a variable frequency synthesizer, which sources the carrier frequency of interest. In the modulation section of a transmitter device, this output carrier frequency and a baseband (data) signal are combined to produce a modulated carrier, which is then filtered by the carrier tracking filter.

The tunable transconductance of the transconductance stage-capacitance filter is referenced to a current mirror circuit, which replicates the control current for the variable synthesizer, and includes a differentially connected pair of matched bipolar transistors, each of which has an effective transconductance g_m . The base electrodes of the differentially connected bipolar transistor pair are coupled to receive complementary input voltages that are centered around a common mode reference voltage level, and have their emitters coupled in circuit with respective controlled (emitter degeneration) MOSFET-implemented resistors. The gate electrodes of the MOSFET-implemented resistors are coupled in common to receive a control voltage that is derived from the transconductance tuning network, which operates the MOSFETs in the linear portion of their $V_{DS}-I_{DS}$ characteristic.

The control voltage for the MOSFET-implemented resistors of the tunable transconductance stage is derived from a tuning network having a servo-loop connected, differential amplifier. A first input of the differential amplifier is coupled to a node between a fixed current source and a reference resistor, which is coupled in circuit with the emitter of a bipolar transistor. The fixed current source is preferably a PTAT reference current, so as to effectively eliminate temperature dependence. The current may be defined by the

ratio of a voltage and a current-setting resistor comprised of the same resistor material as the reference resistor. A second input of the differential amplifier is coupled to a node between a mirrored current source, which supplies current having a magnitude that is a multiple (fractional or whole) of the oscillator control current and the source of a controlled MOSFET-implemented resistor that is coupled in circuit with the emitter of a bipolar transistor.

The bipolar transistors, to which the resistor inputs to the differential amplifier are coupled, are formed in the same integrated circuit chip as the tunable transconductance stage and are matched with its bipolar transistors. The controlled MOSFET-implemented resistor is configured identically to the MOSFET-implemented resistors of the tunable transconductance stage and has its gate electrode coupled to the output of the differential amplifier.

In operation, with a fixed current being supplied through the reference resistor to the first input of the differential amplifier and, with a mirrored, frequency synthesizer control current supplied through the MOSFET-implemented resistor to the second input of the differential amplifier, for a balanced servo loop condition, the two input voltages supplied to the respective inputs of the differential amplifier are equal.

Analysis reveals that the controlled resistance R_m of each of the MOSFET-implemented resistors of the tunable transconductance stage is inversely proportional to the frequency synthesizer's control current. In addition, the transconductance g_m of each of the bipolar transistors of the transconductance stage is dependent upon the value of the bias current supplied by the current mirror circuit, such that the overall effective transconductance G_m of the tunable transconductance stage is linearly proportional to the bias (mirrored synthesizer control) current.

Since the current-controlled oscillator of the synthesizer's phase locked loop produces an output frequency that is linearly proportional to the oscillator control current and inversely proportional to a reference voltage and a frequency-setting capacitor, then, for a phase locked condition, where the phase locked loop's oscillator frequency is equal to the carrier frequency, the cutoff frequency of the tracking filter will be linearly proportional to the carrier frequency, and effectively independent of absolute processing parameters, and temperature variations.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 diagrammatically illustrates the general configuration of a variable carrier frequency communication signal modulator arrangement employing the tracking filter of the present invention;

FIG. 2 diagrammatically illustrates a continuous time tunable g_m/C integrator, of the type commonly employed in high frequency telecommunication signal processing integrated circuit architectures;

FIG. 3 diagrammatically illustrates a cascaded arrangement of the tunable g_m/C integrator stages of FIG. 2;

FIG. 4 diagrammatically illustrates a tunable transconductance stage of the tracking filter of the present invention; and

FIG. 5 diagrammatically illustrates a tuning network for tuning the tunable transconductance stage of the tracking filter of the present invention.

DETAILED DESCRIPTION

FIG. 1 diagrammatically illustrates the general configuration of a tracking filter of the present invention and its

incorporation into a post-modulator signal path location of a variable carrier frequency communication signal modulator arrangement (such as a quadrature modulator arrangement having in-phase I and quadrature Q channels, as a non-limiting example). A modulator (mixer/multiplier) stage **10** of a respective channel, such as the I channel, has a first input **11**, to which a baseband signal of interest is applied, and a second input **13**, which is coupled to receive a carrier frequency signal generated at the output **21** of a variable frequency synthesizer **20**. Modulator stage **10** also has an output **15**, from which the modulated carrier signal of interest is produced. The modulated carrier signal is applied to an input of a variable tracking filter **30**, of a turnable filter stage that includes a transconducted tunin stage **40**. The variable tracking filter **30** is operative to remove the unwanted spurious energy signals from the modulated carrier, as will be described.

Variable frequency synthesizer **20** is of conventional construction, preferably employing a phase locked loop (PLL) having a current-controlled oscillator that produces an output (carrier) frequency f_c , which is linearly proportional to a control current I_{osc} applied to a control input **23**. Synthesizer **20** may include an emitter-coupled multivibrator, whose output frequency is directly proportional to the control current and inversely proportional to a bandgap or PTAT-based reference voltage (which sets the oscillator output amplitude) and a frequency-setting capacitor. (A non-limiting example of such a synthesizer is described on page 570 of the text: "Bipolar and MOS Analog I.C. Design," by Alan B. Grebene, Wiley Publ. 1984.)

As will be described, the carrier-tracking filter mechanism of the present invention makes use of this frequency synthesizer control current I_{osc} to adjust MOSFET-based resistances for establishing the transconductance properties of a tracking filter transconductance tuning stage **40**, which has an input **41** coupled to receive a replica of the control current I_{osc} from a current mirror circuit **25**, such that the cutoff frequency f_o of the transconductance-based tracking filter **30** 'tracks' the carrier frequency f_c as the carrier frequency f is varied in direct linear proportion to the control current I_{osc} .

For this purpose, current mirror circuit **25** is coupled in circuit with the current control path of the variable frequency synthesizer **20**, so that, in addition to supplying the variable carrier frequency f_c at its output **21** for application to baseband modulator stage **10**, variable frequency synthesizer **20** also supplies a replica of the control current I_{osc} at a current mirror output **27** for application to transconductance tuning stage **40**.

Tracking filter stage **30** comprises a continuous time filter circuit, in particular a tunable g_m/C filter, of the type commonly employed in high frequency telecommunication signal processing integrated circuit architectures. As diagrammatically illustrated in FIG. 2, the fundamental building block of such a tunable g_m/C filter is an integrator stage **50**, which is formed of a combination of a transconductance (g_m) stage **51** and a load element, in particular an integrating capacitor (C_L) **53**. The transconductance (g_m) stage **51** contains a transconductance element which produces an output current I_{gm} , that is proportional to an input control voltage V_{in} applied to input terminal **52**. With the output current I_{gm} of transconductance stage **51** being applied to an output terminal **54**, to which the load capacitor (C_L) **53** is coupled and from which an output voltage V_{out} is derived, the transfer function of the integrator stage **50** of FIG. 2 may expressed as a proportionality of g_m to C_L , as by the equation:

$$V_{out}/V_{in} \propto g_m/C_L. \quad (1)$$

By connecting multiple integrators and transconductances, as diagrammatically illustrated at 51-1 and 51-2 in FIG. 3, a transconductance-C ($g_m C$) filter of a desired order may be realized, having a cutoff frequency f_o that is effectively proportional to the ratio of g_m to C.

Namely,

$$f_o g_m / C \quad (2)$$

By using the circuitry of FIG. 4, to be described, to implement the transconductance tuning stage 40 of FIG. 1, the transconductance component g_m can be tuned in relation to the control current I_{osc} employed to establish the carrier frequency f_c of the variable frequency synthesizer 20, such that the filter's cutoff frequency is proportional to or linearly tracks variations in the control current I_{osc} .

More particularly, the tunable transconductance stage of FIG. 4 is comprised of a matched differential bipolar transistor pair comprised of a first bipolar (NPN) transistor 61 and a second bipolar (NPN) transistor 71, each of which has an effective transconductance of g_m . Bipolar transistors 61 and 71 have their respective emitters 62 and 72 coupled to first and second controlled (emitter degeneration) resistors, shown as MOSFET transistors 81 and 91. The respective collectors 63 and 73 of the first and second bipolar transistors 61 and 71 are coupled to a reference voltage rail 78, while their respective base electrodes 64 and 74 are coupled to receive complementary input voltages V_{in+} and V_{in-} , that are centered around a common mode reference voltage level V_{cm} .

MOSFET transistors 81 and 91, which are operated in the linear portion of their $V_{DS}-I_{DS}$ characteristic to provide the intended controlled resistance characteristics to be described, have their drain electrodes 82 and 92 respectively coupled in circuit with the emitters 62 and 72 of transistors 61 and 71, and their source electrodes 83 and 93 coupled in common to the drain electrode 102 of MOSFET 101 of a current mirror circuit 100. The gate electrodes 84 and 94 of respective MOSFETs 81 and 91 are coupled in common to a control voltage line 80, to which a control voltage V_c is applied from the transconductance tuning network of FIG. 5, to be described.

Current mirror circuit 100 includes a further MOSFET 111 having its source electrode 113 connected in common with the source electrode 103 of MOSFET 101. The respective gate electrodes 104 and 114 of MOSFETs 101 and 111 are coupled in common with the drain electrode 115 of MOSFET 111, to which the control current I_{osc} for frequency synthesizer 20 is applied. With each of the various system components being formed on the same semiconductor chip, so that the geometries of like components matching one another, the commonly connected source electrodes 103 and 113 of respective MOSFETs 101 and 111 are effectively coupled to the same current source I_{osc} as is employed to set the output frequency of synthesizer 20.

As noted above, the control voltage V_c is produced from the tuning network of FIG. 5, which comprises a servo-loop connected, differential amplifier 120 having first (+) and second (-) inputs 121 and 122, respectively and an output 123 (from which the control voltage V_c is derived, as will be explained). The first input 121 of differential amplifier 120 is coupled to a node 131 between fixed current (I_f) source 130 and a reference resistor 132, having a reference resistor value of R_o coupled in circuit with the emitter 142 of a bipolar (NPN) transistor 140.

As a non-limiting example, the fixed current source 130 may comprise a PTAT-based current source for temperature

independence, or a bandgap-based reference current source, with the value of I_f defined as:

$$I_f = V_{bg} / R_{set} \quad (3)$$

where V_{bg} is a bandgap voltage (on the order of 1.25 volts), and

R_{set} is a current-setting resistor comprised of the same resistor material as, and therefore effectively identical to the sheet resistivity of the reference resistor 132.

The second input 122 of the differential amplifier 120 is coupled to a node 151 between a mirrored current source 150, which supplies a current $I_{osc}/2$, having a magnitude that is half that of the oscillator control current I_{osc} , and the source electrode 152 of a controlled MOSFET-implemented resistor 153, coupled in circuit with the emitter 162 of a bipolar (NPN) transistor 160.

Bipolar transistors 140 and 160, being formed in the same integrated circuit chip as the tunable transconductance stage of FIG. 4, are matched with bipolar transistors 61 and 71, and have their respective base electrodes 144 and 164 supplied with the common mode input voltage level V_{cm} , referenced above, via control lead 149. The respective collector electrodes 143 and 163 are coupled to a V_{cc} supply rail 168.

The controlled MOSFET-implemented resistor 153 is configured identically to MOSFETs 101 and 111 of the tunable transconductance stage of FIG. 4, and has its gate electrode 154 coupled to receive the control voltage V_c at the output 123 of differential amplifier 120. The drain electrode 155 of MOSFET resistor 153 is coupled to the emitter 162 of bipolar transistor 160.

In operation, with a fixed current I_f being supplied by way of current source 130 through reference resistor 132, and with a mirrored current $I_{osc}/2$ being supplied by way of current source 150 through MOSFET resistor 153, for a balanced servo loop condition, the two input voltages supplied to the respective inputs 121 and 122 of differential amplifier 120 are equal. Namely,

$$R_m * I_{osc} / 2 = R_o * I_f \quad (4)$$

From equation (4), the resistor value R_m of controlled MOSFET resistor 153 can be written as:

$$R_m = R_o * 2 I_f / I_{osc} \quad (5)$$

Substituting the value of I_f from equation (3), the value of R_m can be expressed as:

$$R_m = k_o / I_{osc} \quad (6)$$

where $k_o = 2 V_{bg} * (R_o / R_{set})$, and is essentially a constant, since it is proportional to the product of a fixed bandgap voltage and the ratio of resistors of the same wafer material.

Thus, equation (6) reveals that the controlled resistance R_m of each of MOSFETs 101 and 111 in the tunable transconductance stage of FIG. 4 is inversely proportional to the frequency synthesizer control current I_{osc} .

The overall effective transconductance G_m of the differential pair-implemented tunable transconductance stage of FIG. 4 is given by the expression:

$$G_m = 2 g_m / (2 + 2 g_m R_m) \quad (7)$$

The transconductance g_m of each of bipolar transistors **61** and **71** is dependent upon the value of the bias current I_{osc} supplied by current mirror circuit **100**, such that

$$g_m = (q/kT) * (I_{osc}/2). \quad (8)$$

By combining equations (6), (7) and (8), the overall effective transconductance G_m of the tunable transconductance stage of FIG. 4 can be expressed as

$$G_m = (qI_{osc}/kT) / (2 + (q/k_0)/kT), \quad (9)$$

which reveals that G_m is linearly proportional to the bias current I_{osc} .

As noted earlier, in the frequency synthesizer **20** of FIG. 1, the current-controlled oscillator of the synthesizer's PLL may employ an emitter-coupled multivibrator, whose output frequency is linearly proportional to the control current (I_{osc}) and inversely proportional to a bandgap based reference voltage (V_{ref}) and a frequency-setting capacitor (C_o).

From the above-referenced Grebene text, the oscillator output frequency f_{osc} may be written as:

$$f_{osc} = I_{osc} / 4V_{ref}C_o. \quad (10)$$

For a phase locked condition, where the PLL oscillator frequency f_{osc} is equal to the carrier frequency f_c , the required oscillator control current I_{osc} in equation (10) thus becomes:

$$I_{osc} = 4V_{ref}f_cC_o. \quad (11)$$

Combining equations (2), (9) and (11) to derive an expression for the cutoff frequency f_o yields:

$$f_o G_m / C = (4V_{ref}f_c(q/kT)C_o/C) / (2 + qk_0/kT). \quad (12)$$

Thus, with the exception of T and f_c , all the terms in equation (12) are constants. The temperature-dependency term T can be readily eliminated by using a PTAT-based current source as the current source **130** in the tuning circuit of FIG. 5 (instead of a bandgap source used to simplify the derivation). Equation (12) thus becomes:

$$f_o K_1 * f_c * (C_o/C), \quad (13)$$

where K_1 is a constant proportional to V_{ref} and independent of temperature.

This establishes that the cutoff frequency f_o of a transconductance stage-based tracking filter of the invention, comprised of the tunable transconductance stage of FIG. 4 and the tuning network of FIG. 5, is effectively independent of process parameters (other than geometry ratios of like (matched) components, as described above), independent of temperature, and is linearly proportional to the carrier frequency f_c .

As will be appreciated from the foregoing description, the impracticality of attempting to implement a spurious energy suppression filter as an unacceptably large order noise suppression filter for a data communication system is successfully addressed by the post-mixer tracking filter of the present invention, configured as a current-controlled MOSFET-implemented resistance for a transconductance-capacitance filter and an associated transconductance tuning stage, with the MOSFET-implemented resistance being controlled by the same control current that establishes the output frequency. As a consequence, the cut-off frequency of the filter effectively tracks the carrier, and effectively independent of absolute processing parameters and temperature.

While we have shown and described an embodiment in accordance with the present invention, it is to be understood that the same is not limited thereto but is susceptible to numerous changes and modifications as known to a person skilled in the art, and we therefore do not wish to be limited to the details shown and described herein but intend to cover all such changes and modifications as are obvious to one of ordinary skill in the art.

What is claimed is:

1. A frequency-tracking filter circuit for a communication device having a frequency synthesizer and current-controlled oscillator circuit which generates an output frequency in linear proportion with a control current therefor, comprising a tunable filter stage, operational characteristics of which are controllable in accordance with said control current, such that said tunable filter stage has a cut-off frequency that is linearly proportional to said control current, wherein said tunable filter stage comprises a tunable transconductance-containing filter stage and a transconductance tuning stage coupled thereto, operational characteristics of said tunable transconductance containing filter stage and said transconductance tuning stage being controllable in accordance with said control current in such a manner that said tunable transconductance containing filter stage has a cut-off frequency that is linearly proportional to said control current.

2. A frequency-tracking filter circuit according to claim 1, wherein said tunable transconductance-containing filter stage comprises a tunable g_m/C filter, having at least one tunable transconductance (g_m) stage and integrating capacitor C coupled therewith, such that said tunable g_m/C filter has a cutoff frequency f_o proportional to the ratio of g_m to C .

3. A frequency-tracking filter circuit according to claim 2, wherein said tunable transconductance (g_m) stage is referenced to a current mirror circuit, which replicates said control current.

4. A frequency-tracking filter circuit according to claim 3, wherein said tunable transconductance (g_m) stage includes a differentially connected pair of bipolar transistors, each having an effective transconductance g_m , and being coupled in circuit with a respective controlled MOSFET-implemented resistance, which is coupled to receive a control input derived from said transconductance tuning stage.

5. A frequency-tracking filter circuit according to claim 4, wherein each MOSFET-implemented resistance is operated in the linear portion of its $V_{DS}-I_{DS}$ characteristic.

6. A frequency-tracking filter circuit according to claim 4, wherein each MOSFET-implemented resistance of said tunable transconductance stage has a controlled resistance that is inversely proportional to said control current.

7. A signal processing circuit comprising a tunable transconductance-based filter stage and a transconductance tuning stage coupled thereto, and wherein transfer functions of each of said tunable transconductance-based filter stage and said transconductance tuning stage coupled thereto are based upon a common control current and are interconnected such that said tunable transconductance-based filter stage has a cut-off frequency that is linearly proportional to said common control current, wherein said common control current is derived from a control current for controlling an output frequency generated by a variable frequency synthesizer, and said output frequency generated by said variable frequency synthesizer is coupled to a modulation section of a transmitter device, which is operative to combine said output frequency with a baseband signal to produce a modulated frequency signal, said modulated frequency signal being coupled to a tunable g_m/C filter, having

a tunable transconductance (g_m) stage and integrating capacitor C coupled therewith, such that said tunable g_m/C filter has a cut-off frequency f_o proportional to the ratio of g_m to C.

8. A signal processing circuit according to claim 7, 5 wherein said tunable transconductance and said transconductance tuning stage are interconnected such that said tunable g_m/C filter has a cut-off frequency that is linearly proportional to said control current.

9. A signal processing circuit according to claim 7, 10 wherein said tunable transconductance (g_m) stage is referenced to a current mirror circuit, which replicates said control current.

10. A signal processing circuit according to claim 9, 15 wherein said tunable transconductance (g_m) stage includes a differentially connected pair of bipolar transistors, each having an effective transconductance g_m , and being coupled in circuit with a respective controlled MOSFET-implemented resistance, which is coupled to receive a control input derived from said transconductance tuning stage. 20

11. A signal processing circuit according to claim 10, wherein each MOSFET-implemented resistance is operated in its linear region.

12. A signal processing circuit according to claim 8, 25 wherein each MOSFET-implemented resistance of said tunable transconductance stage has a controlled resistance that is inversely proportional to said control current.

13. A method of controlling a transconductance circuit comprising the steps of:

(a) providing a transconductance tuning stage which is 30 operative to produce a variable control output in accor-

dance with a control current supplied to said transconductance tuning stage by generating said control current based upon a control current for controlling an output frequency generated by a variable frequency synthesizer; and modulating said output frequency generated by said variable frequency synthesizer with a baseband signal to produce a modulated frequency signal, and applying said modulated frequency signal to a tunable transconductance-containing filter stage containing said transconductance circuit and an integrating capacitor coupled therewith; and

(b) varying the transconductance of said transconductance circuit in linear proportion to said variable control output produced by said transconductance tuning stage.

14. A method according to claim 13, wherein said transconductance circuit includes a differentially connected pair of bipolar transistors, each having a transconductance g_m , and being coupled in circuit with a respective controlled MOSFET-implemented resistance, and step (b) comprises varying each controlled MOSFET-implemented resistance in accordance with said variable control output produced by said transconductance tuning stage.

15. A method according to claim 14, wherein step (b) further comprises operating each MOSFET-implemented resistance in its linear region.

16. A method according to claim 14, wherein each MOSFET-implemented resistance of said transconductance circuit has a controlled resistance that is inversely proportional to said control current.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 6,233,293 B1
DATED : May 15, 2001
INVENTOR(S) : Brent A. Myers and Paul J. Godfrey

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 4,

Line 14, delete "tunin" insert -- tuning --

Line 15, delete "traching" insert -- tracking --

Line 67, delete "Vout/Vin g_m/C_L ." insert -- $V_{out}/V_{in} \propto g_m/C_L$. --

Column 7,

Line 35, delete " $f_o G_m/C = (4V_{ref}f_c(q/kT) C_o/C) / (2 + qk_o/kT)$." insert -- $f_o \propto G_m/C = (4V_{ref}f_c(q/kT) C_o/C) / (2 + qk_o/kT)$. --

Line 43, delete " $f_o K_1 * f_c * (C_o/C)$," insert -- $f_o \propto K_1 * f_c * (C_o/C)$, --

Signed and Sealed this

Ninth Day of April, 2002

Attest:



Attesting Officer

JAMES E. ROGAN
Director of the United States Patent and Trademark Office